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Evaluating the performance of a relative humidity-based warning system for sooty blotch and flyspeck in Iowa

Hafizi Bin Rosli
Iowa State University, hafizi@iastate.edu

Derrick A. Mayfield
Iowa State University, damayfie@iastate.edu

Jean C. Batzer
Iowa State University, jbatzer@iastate.edu

Philip M. Dixon
Iowa State University, pdixon@iastate.edu

Wendong Zhang
Iowa State University, wdzhang@iastate.edu

See next page for additional authors

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Abstract

A warning system for the sooty blotch and flyspeck (SBFS) fungal disease complex of apple, developed originally for use in the southeastern United States, was modified to provide more reliable assessment of SBFS risk in Iowa. Modeling results based on previous research in Iowa and Wisconsin had suggested replacing leaf wetness duration with cumulative hours of relative humidity (RH) >=97%as the weather input to the SBFS warning system. The purpose of the present study was to evaluate the performance of a RH based SBFS warning system, and to assess the potential economic benefits for its use in Iowa. The warning system was evaluated in two separate sets of trials—trial 1 during 2010 and 2011, and trial 2 during 2013–2015—using action thresholds based on cumulative hours of RH >=97% and >=90%, respectively, in conjunction with two different fungicide regimes. The warning system was compared with a traditional calendar-based system that specified spraying at predetermined intervals of 10 to 14 days. In trial 1, use of the RH $97% threshold caused substantial differences between two RH sensors in recording number of hours exceeding the threshold. When both RH thresholds were compared for 2013–2015, on average, RH >=90% resulted in a 53% reduction in variation of cumulative hours between two identical RH sensors placed adjacent to each other in an apple tree canopy. Although both the SBFS warning system and the calendar-based system resulted in equivalent control of SBFS, the warning system required fewer fungicide sprays than the calendar-based system, with an average of 3.8 sprays per season (min = 2; max = 5) vs. 6.4 sprays per season (min = 5; max = 8), respectively. The two fungicide regimes provided equivalent SBFS control when used in conjunction with the warning system. A partial budget analysis showed that using the SBFS warning system with a threshold of RH>=90%was cost effective for orchard sizes of >1 ha. The revised warning system has potential to become a valuable decision support tool for Midwest apple growers because it reduces fungicide costs while protecting apples as effectively as a calendar-based spray schedule. The next step toward implementation of the SBFS warning system in the North Central U.S. should be multiyear field testing in commercial orchards throughout the region.

Keywords

Integrated pest management, relative humidity, decision support systems, diseaseforecasting, binomial for apple

Disciplines

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Authors

Hafizi Bin Rosli, Derrick A. Mayfield, Jean C. Batzer, Philip M. Dixon, Wendong Zhang, and Mark L. Gleason

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Hafizi Rosli[1,2], Derrick A. Mayfield[1], Jean C. Batzer[1], Philip M. Dixon[3], Wendong Zhang[4] & Mark L. Gleason[1]

[1]Department of Plant Pathology and Microbiology, Iowa State University, Ames IA, USA

[2]School of Biological Sciences, Universiti Sains Malaysia, Penang, Malaysia

[3]Department of Statistics, Iowa State University, Ames IA, USA

[4]Department of Economics, Iowa State University, Ames IA, USA

Corresponding author: Mark L. Gleason

E-mail address: mgleason@iastate.edu

Abstract

A warning system for the sooty blotch and flyspeck (SBFS) fungal disease complex of apple, developed originally for use in the southeastern United States, was modified to provide more reliable assessment of SBFS risk in Iowa. Modeling results based on previous research in Iowa and Wisconsin had suggested replacing leaf wetness duration with cumulative hours of relative humidity (RH) ≥97% as the weather input to the SBFS warning system. The purpose of the present study was to evaluate the performance of a RH-based SBFS warning system, and to assess the potential economic benefits for its use in Iowa. The warning system was evaluated in two separate sets of trials - Trial 1 during 2010 and 2011, and Trial 2 during 2013-2015 - using action thresholds based on cumulative hours of RH ≥97% and ≥90%, respectively, in conjunction with two different fungicide regimes. The warning system was compared to a traditional calendar-based system that specified spraying at predetermined intervals of 10 to 14 days. In Trial 1, use of the RH ≥97% threshold caused substantial differences between two RH sensors in recording number of hours exceeding the threshold. When both RH thresholds were compared for 2013-2015, on average, RH ≥90% resulted in a 53% reduction in variation of cumulative hours between two identical RH sensors placed adjacent to each other in an apple tree canopy. Although both the SBFS warning system and the calendar-based system resulted in equivalent control of SBFS, the warning system required fewer fungicide sprays than the calendar-based system, with an average of 3.8 sprays per season (min = 2; max = 5) *vs*. 6.4 sprays per season (min = 5; max = 8), respectively. The two fungicide regimes provided equivalent SBFS control when used in conjunction with the warning system. A partial budget analysis showed that using the SBFS warning system with a threshold of RH ≥90% was cost effective for orchard sizes of >1 hectare. The revised warning system has potential to become a valuable decision support tool for Midwest apple growers because it reduces fungicide costs while protecting apples as effectively as a calendar-based spray schedule. The next step toward implementation of the SBFS warning system in the North Central U.S. should be multi-year field testing in commercial orchards throughout the region.

Keywords: Integrated pest management, relative humidity, decision support systems, disease forecasting, binomial for apple

Introduction

Sooty blotch and flyspeck (SBFS) is a fungal disease complex that affects apple, pear, and several other tree fruit crops in moist growing regions worldwide (Gleason et al. 2011, Williamson and Sutton 2000). The SBFS infections are superficial black blemishes or clusters of tiny dots on the fruit surface. Economic losses on apple, in particular, can be severe when SBFS-blemished fruit are downgraded from fresh market to processing use (Gleason et al. 2011; Williamson and Sutton 2000).

In U.S. apple orchards, the prevailing management strategy against SBFS is application of fungicide sprays at intervals of 7 to 14 days during the fruit maturation period. This preventive program, which does not explicitly gauge the level of weather-related risk posed by SBFS, generally provides consistent control of SBFS but can result in over-application of fungicides and exacerbate human health risks from exposure to certain fungicides (Capriglione et al. 2011; Li et al. 2009). Consequently, weather-based warning systems were developed to help growers to achieve SBFS control more cost-effectively and with less health risk.

The first SBFS warning system, developed for apple growers in the southeastern U.S. (North Carolina and Kentucky), based timing of the second-cover fungicide spray on cumulative hours of leaf wetness duration (LWD) after the first-cover spray (Brown and Sutton 1995; Hartman 1995). This Brown-Sutton-Hartman warning system enabled growers in that region to save an average of two to three fungicide sprays per summer without compromising control of SBFS. However, when this system was trialed with commercial apple growers in the Upper Midwest U.S. (Illinois, Iowa, and Wisconsin), high incidence of SBFS blemishes on fruit occurred in 12 of 28 site-years, which was unacceptable to the growers (Babadoost et al. 2004). Spolti et al. (2011) later validated the Brown-Sutton-Hartman system for three years in Brazil. The 2006-2008 studies found that the system was able to save some fungicide sprays and worked equally well with the conventional calendar-based system in controlling SBFS. In an attempt to recalibrate the Brown-Sutton-Hartman warning system for use in the Upper Midwest, Duttweiler and co-workers (2008) assessed ability of measurements of several weather variables to predict the timing of first appearance of SBFS colonies on apples. Based on assessment of 19 site-years of field work by receiver operating characteristic curve analysis, they concluded that cumulative hours of relative humidity (RH) ≥97% was a more accurate predictor than cumulative LWD in predicting the first appearance of SBFS in Iowa and Wisconsin. However, this Gleason-Duttweiler warning system requires evaluation of its performance in Upper Midwest orchards before any recommendation for system adoption can be made. The objective of the present study was to evaluate the performance of a RH-based warning system for SBFS, and to assess the economic benefits of the proposed warning system. We also compared efficacy of conventional and reduced-risk fungicides when used in conjunction with the warning system.

Materials and Methods:

Field site. Two separate trials were conducted during 2010 to 2011 (Trial 1) and 2013 to 2015 (Trial 2) at the Iowa State University Horticulture Research Station (ISUHRS; 42°06'23.8"N, 93°35'23.3"W). The 0.52-ha apple orchard, planted in 1989, incorporated randomly arranged five-tree subplots of cvs. Golden Delicious, Red Delicious, Jonathan, and McIntosh on M7 rootstock. Spacing was 3.7 m between rows and 7.6 m within rows (Supplementary Figure S1).

RH threshold. Two RH thresholds were evaluated. Trial 1 assessed the SBFS warning system proposed by Duttweiler et al. (2008), which delayed application of the second-cover fungicide spray until 192 cumulative hours of RH ≥97% had elapsed since the first-cover spray. Once the second-cover spray had been applied, subsequent fungicide sprays were timed according to a calendar-based system (Brown and Sutton 1995; Hartman 1995; Babadoost et al. 2004). Based on findings from Trial 1 (Table 1; discussed in Results), the experimental design was modified for Trial 2 (2013-2015). The threshold criterion used in the SBFS warning system was changed from cumulative hours of RH ≥97% to cumulative hours of RH ≥90% because, field data obtained during Trial 1 from paired sensors indicated that variability between sensors in recording hours of RH was reduced by approximately 55% if the threshold was reduced from 97% to 90% (Mayfield 2013). Furthermore, the specification of the RH sensor provided by the manufacturer stated that accuracy was ±3% for RH ranging from 10 to 90% and ±5% for RH outside that range (www.specmeters.com). Decreasing sensor-to-sensor variability was judged to be important in assuring reliable performance of the warning system. Based on analysis of field data from paired RH sensors in the ISUHRS orchard during the 2011 growing season (Mayfield 2013), the number of hours of RH ≥90% required to trigger the second-cover fungicide spray in the warning system was set at 385. Relative humidity measurements for both trials were made hourly by two WatchDog A-Series weather monitors (WatchDog Model A150 Temp/RH Logger, Spectrum Technologies, Plainfield, IL, USA) that were positioned adjacent to each other within a tree canopy in the center of the test plot at 1.5-m height (Duttweiler et al. 2008).

Treatments. The experimental design for Trial 1 included five treatments (Table 1). Three treatments used the warning system in conjunction with different fungicide regimes: trifloxystrobin (Flint®), a premix of pyraclostrobin and boscalid (Pristine®), and traditional summer fungicides (Captan plus thiophanate-methyl (Topsin® M 4.5FL)). The fourth treatment was a calendar-based control that specified applying Captan and Topsin® M every 10 to 14 days from first-cover until 1 week before harvest, whereas the fifth treatment was an unsprayed control treatment (no fungicide sprays after first-cover). In the warning system treatments, the reduced-risk fungicides Flint® and Pristine® were used only for first- and second-cover sprays; the combination of Captan plus Topsin® M was used for the subsequent sprays at 10- to 14-day intervals until harvest. According to the U.S. EPA, reduced-risk fungicides pose less risk to human health and the environment compared to conventional fungicides (www.epa.gov). Subplots, each consisting of five adjacent trees of the same cultivar (Golden Delicious, Red Delicious, Jonathan, or McIntosh), were arranged in a completely randomized design, with five replications (subplots) of each treatment per cultivar. For Trial 2, we modified the treatments, evaluating both warning system and calendar-based system with the same fungicide regimes. Four treatments incorporated combinations of two spray timing treatments (the modified SBFS warning system and the calendar-based system) and two fungicide regimes (one using Captan plus Topsin® M and the other using Captan plus either Flint® or potassium phosphite (Prophyt®)) (Table 2). A fifth (control) treatment received no fungicide sprays after first-cover was included as the fifth treatment. The five treatments were randomly assigned within the cultivars, with each treatment replicated in five to six subplots. To control non-target diseases such as apple scab (*Venturia inaequalis*) and rusts (*Gymnosporangium* spp.), all treatments in both Trial 1 and 2 were sprayed with a tank mix of mycobutanil (Rally® 40 WSP) and fenarimol (Rubigan®) from green tip through petal fall, and a tank mix of Topsin® M plus Captan was used as the first-cover spray. All fungicide spray treatments were ended when the first apple cultivar was harvested. All pesticides were applied using an air blast sprayer (John Bean Redline Model 328 Air Sprayers, LaGrange, GA) at 2068 kPa.

Data collection and analysis: At the end of growing season on both Trial 1 and Trial 2, 50 apples per tree were sampled arbitrarily at harvest from the center three trees of each subplot, including 25 apples from the top half of the canopy and 25 from the bottom half of the canopy of each tree. Incidence of SBFS (% apples with visible colonies) was calculated for each tree, then log-transformed (natural log) to reduce the unequal variation observed in the original data. We considered a generalized linear mixed model for binomial data. There was substantial overdispersion and the amount of overdispersion on the logit link scale differed among treatments. The log transformation did a better job of controlling unequal variation than logit transformation. For Trial 2 data analysis, in addition to SBFS incidence data, percent marketable apples (arbitrarily defined as apples with <2% surface coverage by SBFS colonies) was also determined by using a standard area diagram of SBFS colonization (Batzer et al. 2002). PROC GLIMMIX (SAS Inc., Durham, NC) was used with treatment and cultivar as the fixed effects. The subplot identifier (replicate × treatment × cultivar) was included as a random effect. Least Squares Means (LSM) was used to assess significance of differences among treatments.

Economic analysis. We used data from Trial 2 to conduct a partial budget analysis (Calkins and Dipietre 1983) to assess the cost and economic efficiency of the warning system relative to the conventional calendar-based system, incorporating the cost of both the weather monitoring equipment and its operation (Table 5, discussed in Results). In this analysis, we used an "equivalent annual cost" (EAC) approach to convert the one-time purchase cost of the devices used for RH monitoring to the annual cost of owning, operating, and maintaining this system for a 3-year life expectancy (Table 3). We also simulated the total cost for orchards of different sizes ranging from 1 to 50 hectares, and assumed that for orchard sizes >5 hectares, four RH sensors rather than two would be required. We assessed the economic efficiency of the warning system in SBFS management using two measures: average cost ratio and relative cost-efficiency ratio (Tan-Torres Edejer et al. 2003; Polasky et al. 2011) (Table 3). The average annual cost ratio was constructed by averaging the cost of the warning system using conventional fungicides with that using reduced-risk fungicides, then dividing this average cost by a calculated average cost across the two calendar-based system treatments during the same growing season. A cost ratio

<1 would suggest that for a particular size of orchard, the warning system on average had a lower cost than the calendar-based system. A cost-efficiency ratio expresses the average increase in the percentage of marketable apples for an additional dollar increase in the per-hectare production cost. We constructed a relative cost-efficiency ratio to compare the warning system to the calendar-based system for each year. A ratio >1 indicated that the warning system had better economic performance (lower cost to produce the same marketable apple) than the calendar-based system.

Results:

RH threshold. Using the SBFS warning system with the RH ≥97% threshold resulted in three and two fewer fungicide sprays in 2010 and 2011, respectively (Table 1), with SBFS control equivalent to that from using the calendar-based spray timing treatment. Used in conjunction with either the warning system or the calendar-based system, both Flint® and Pristine® provided SBFS control equivalent to that provided by Captan and Topsin® M. In 2013-2015 (Trial 2), using the warning system with the RH ≥90% threshold resulted in control SBFS as effectively as the calendar-based system; the number of sprays saved per year ranged from one in 2014 and two in 2015 - both exceptionally wet years - to five in the exceptionally dry year of 2013 (Tables 2 and 4). On average, the timing of occurrence of RH ≥90% thresholds recorded by the two paired sensors differed by 10.2 hours; the smaller differences occurred in 2014 and 2015 with 1 and 1.5 hours, respectively. When the RH ≥97% threshold was evaluated using the Trial 2 RH data, we found that on overage, the two paired sensors were 21.8 cumulative hours apart in reaching the threshold; the largest difference occurred in in 2014 with 44.3 cumulative hours difference (Rosli, unpublished data). We also used the Trial 2 data to assess how the SBFS warning system performance would differ if the RH ≥97% threshold was used instead of RH ≥90% threshold; the RH ≥97% threshold was reached earlier than the RH ≥90% threshold by 27 days in 2013, 10 days in 2014, and 9 days in 2015 (Table 4).

SBFS suppression. Incidence of SBFS for both Trials 1 and 2 varied among years depending on prevailing weather patterns. Overall, SBFS was highest for the no-spray control treatment (Supplementary Tables S1 and S2). The log SBFS incidence did not differ significantly between warning-system and calendar-based treatments in either Trial 1 (Table 1) or Trial 2 (Table 2). When the no-spray control treatment was included in the analysis, SBFS incidence was significantly different among treatments except in the abnormally dry 2013 growing season (Table 2). Apples were rated as 100% marketable in all treatments in 2013, and showed no significant difference for this variable among treatments in 2014. The exceptionally wet year of 2015 resulted in approximately 50% marketable apples in the control treatment, whereas there were no significant differences among warning-system and calendar-based treatments, with percent marketable apple ranging from 98 to 99% (Table 2; Supplementary Figure S2). In order to test equivalent effectiveness of warning-system and calendar-based treatments in controlling SBFS, the statistical analysis was repeated after excluding data from the no-fungicide-spray control treatment in both Trials 1 and 2. The results indicated that the effect was similar to that when the no-spray control treatment was included (Rosli, unpublished data). Of the five growing seasons in the study, only 2013 showed a significant interaction between cultivar and treatment (*P*<0.05). The first harvested cultivar, McIntosh, had the least SBFS incidence, whereas the last-harvested cultivar, Golden Delicious, had the highest SBFS incidence (Rosli, unpublished data).

Economic analysis. The annual cost associated with the warning system in the test plot varied from $285 in 2013 to $364 in 2014 and 2015 (Table 5). Relative humidity sensors and accompanying devices represented the largest expense category. Defraying this quasi-fixed expense required an orchard size large enough to offset these costs, since spray costs were calculated on a per-hectare basis. Figure 1A illustrates the reductions in the relative costs for operating the RH-based warning system in 2013-2015 over the calendar-based system in controlling SBFS at different orchard sizes. On average, using the warning system resulted in input cost savings for an orchard >1 hectare in size, and the benefits increased for larger orchards (Figure 1A). Relative cost-efficiency ratios (Figure 1B) indicated that every dollar invested in operating the RH-based warning system would yields a higher percentage of marketable apples than the calendar-based system. Given that the percentage of marketable apples for any given year did not vary statistically among treatments when excluding the no-fungicide control treatment, this ratio is the reciprocal of the cost ratio shown in Figure 1A. It also revealed that, overall, the warning system was relatively more cost-efficient than the calendar-based system for an orchard >5 hectares in size. The cost efficiency was more apparent during dry year (2013) compared to wet year (2014 and 2015). The simulation of doubling the device cost (four RH sensors rather than two) for orchard sizes >5 hectares showed no apparent differences in either the relative operating cost (Figure 1A) or relative cost efficiency (Figure 1B).

Discussion

This is the first evaluation of the RH-based SBFS warning system initially proposed by Duttweiler et al. (2008). Results of our trials indicate substantive progress in modifying of a SBFS warning system for use by apple growers in the Upper Midwest U.S. Changes to the original Brown-Sutton-Hartman SBFS warning system, which was developed for the considerably different climate of the southeastern U.S., were proposed after modeling weather-

SBFS relationships in Iowa and Wisconsin (Duttweiler et al. 2008). The primary change was that the action threshold for triggering the second-cover fungicide spray in the newly proposed Gleason-Duttweiler warning system was determined by a RH-based criterion rather than LWD as in the Brown-Sutton-Hartman system. In addition to their modeling results, the authors presented a climate-based rationale for opting for RH over LWD: given that 70% of wet hours during Upper Midwest summers are caused by dew *vs.* 70% of wet hours being associated with rainfall in western North Carolina (where the original warning system was developed), and that RH sensor measurements are less sensitive to microsite variation within apple tree canopies during dew periods than LWD sensors (Batzer et al. 2008), using a RH criterion to track duration of wet periods was preferred in the dew-dominated climate of the Upper Midwest (Duttweiler et al. 2008). Trial 1 in the present study established that using the Gleason-Duttweiler warning system could save several fungicide sprays per season while providing SBFS suppression equivalent to calendar-based spray timing.

When analysis of the 2011 data for paired RH sensors positioned at the same location in the orchard revealed substantial sensor-to-sensor variation in determining hours of RH $\geq$97%, we developed a new RH threshold for the warning system - cumulative hours with RH $\geq$90% - and modified the number of hours associated with the new threshold accordingly. The 90% RH threshold had the practical advantage of reducing variability between paired sensors by 55%, which should increase reproducibility of warning system results. In the present study, variability between paired sensors was reduced by approximately 53% when the 90% RH threshold was used in place of the 97% RH threshold. Using a RH threshold of $\geq$90% is widely accepted as a surrogate for leaf wetness (Wilks and Shen 1991; Sentelhas et al. 2008). Several other meteorological studies also found that RH >90% was the preferred threshold for a LWD estimation model and suggested that RH readings were unreliable above 95% (Chen et al. 2012; Kronenberg et al. 2002).

There are >80 named and putative SBFS species, and some of these species have distinct responses to temperature and RH (Gleason et al. 2011; William and Sutton 2000). According to Johnson and Sutton (2000), RH >88% was needed to germinate conidia of all SBFS species they studied. Field studies found that RH ≥90% was positively correlated with the incidence and severity of SBFS symptoms on apple fruit (Sutton and Sutton, 1994). Therefore, apart from the high level of variability among RH sensors at RH ≥97%, evidence from both plant pathology and micrometeorology support our conclusion that RH ≥90% is preferable to RH ≥97% as the threshold for the modified Gleason-Duttweiler warning system.

The apple varieties in our study were harvested over a period of five to six weeks during September and October, with about two weeks between harvest of each variety. Nevertheless, statistically significant interaction between cultivar and treatment occurred in only 1 of the 3 years in Trial 2. Early-maturing cultivars – those that mature in July or early August, four to six weeks before the fall-harvested varieties - often escape SBFS infection, presumably due to insufficient time between fruit inoculation and appearance of visible colonies (Biggs et al. 2010; Gleason et al. 2011). A field study by Biggs et al. (2010), which grouped 23 apple cultivars by harvest date as early season, early mid-season, late mid-season, or late season, found that differences in SBFS incidence were more significant between the harvest-period groups than among cultivars within a group. For practical reasons, therefore, many growers apply the final fungicide spray of the season in an orchard to all cultivars with similar maturity dates.

Modification of disease-warning systems is often necessary before they can be used with confidence outside of the regions in which they were developed. Part of the reason is the need to adjust to different climatic regimes in the new regions. Billing (2007) outlined a step-by-step evaluation protocol when moving weather-based decision-support systems to regions with different climates. A first step is to test the original system specifications. For example: the NegFry system for potato late blight was developed in Germany and tested in Ireland (Leonard et al. 2001); the SIM-CAST, TOM-CAST, and BLITECAST systems for potato late blight, developed in North America, were tested in the Toluca Valley of Mexico (Grünwald et al. 2000, 2002); North American warning systems for fire blight were evaluated in Israel (Shtienberg et al. 2003); and forecast models for Fusarium head blight developed in Italy, Argentina and United States were evaluated in Canada (Giroux et al. 2016). If the original models fail to fit the new climate conditions, modifications should be made and a new model ought to be created; examples include the BIS system (Billing 2007) and the Gleason-Duttweiler warning system (Duttweiler et al. 2008). An additional complicating factor in moving an SBFS warning system among geographic regions is that the assemblage of SBFS species varies regionally (Díaz Arias et al. 2010), which could be important for management because the environmental biology and fungicide sensitivity also differ significantly among SBFS species (Batzer et al. 2012; Ismail et al. 2016; Tarnowski et al. 2003). In addition, further trials can trigger a re-evaluation and modification of originally proposed action thresholds, even within the region where the system was originally developed. For example, Wu et al. (2002) modified the LWD threshold that triggered fungicide sprays in the lettuce downy mildew warning system developed in coastal California (Scherm et al. 1995) to minimize unnecessary sprays, and also added temperature and solar radiation as decision support criteria. In the present case, observations concerning sensor-to-sensor variability in RH measurement led to a lowering of the RH threshold for the Gleason-

Duttweiler warning system.

Even though SBFS risk is higher during wet than dry growing seasons (Gleason et al. 2011), the Gleason-Duttweiler warning system maintained acceptable SBFS control and saved one to five fungicide sprays per season compared to traditional calendar-based timing of the second-cover spray. Spray savings were greater during dry seasons. An average reduction of 2.7 sprays per year translates into less exposure by growers, farm workers, and consumers to potentially hazardous fungicides. As in a previous study (Babadoost et al. 2004) comparing the reduced-risk fungicides kresoxim methyl and trifloxystrobin to the traditional fungicides thiophanate-methyl and Captan, both reduced-risk and traditional fungicides were equally effective in controlling SBFS.

The partial budget analysis showed that commercial apple growers in Iowa and other regions with similar climatic condition could potentially reduce their input costs and improve their economic efficiency by adopting the Gleason-Duttweiler system in their orchard. In particular, the two sub-charts of Figure 1 showcase this improvement from two angles: When the cost ratio in Figure 1A is <1, it suggests for that particular orchard size, the operating cost for the new warning system is on average lower than that for the calendar-based system; and similarly, when the relative cost efficiency ratio shown in Figure 1B is >1, it shows that for that particular orchard size, every dollar invested in the operating costs would yield a higher percentage of marketable apples for the new warning system *vs*. the conventional system. In addition, Figure 1 reveals that the Gleason-Duttweiler system would be more economically efficient than the conventional calendar-based system as the size of the orchard increases, especially beyond 5 hectares; for example, an increase in orchard size from 2 to 10 hectares suggests that the relative cost of the new warning system would change from about 80% to less than 70% of the cost of a calendar-based system.

However, using warning systems entails some additional risks. For example, care in handling and maintaining RH sensors and data loggers can influence data reliability, thereby affecting performance of the warning system (Sutton et al. 1984). Similar maintenance and calibration challenges influence accuracy of LWD sensors (Gleason et al. 2008; Rowlandson et al. 2015). As shown in our simulation, economic advantage from using the warning system was proportional to orchard size; these savings could compensate for the purchase cost of additional sensors and data loggers that could be required for monitoring in larger orchards. Based on Trial 2 results, one hectare was the threshold orchard size above which economics of the SBFS warning system were more advantageous than for the calendar-based system.

The main value of the proposed warning system is to provide an efficient management option for controlling SBFS infection, based on weather conditions that drive the risk of outbreaks. Reducing fungicide use also means reducing the exposure of growers to fungicides that can endanger their health. In addition, reducing reliance on fungicides can improve the competitive position of growers in markets that emphasize minimal-pesticide production. Studies on pesticide residues on apples (Kovacova et al. 2014; Sadło et al. 2016) and the effects on adults, children (Lozowicka 2015; Szpyrka et al. 2013) and the environment (He et al. 2016; Wang et al. 2016) have raised consumer concerns about pesticide contamination of fruit, so reducing fungicide sprays may ease these concerns.

The modified Gleason-Duttweiler warning system could benefit many apple growers in the Upper Midwest U.S. as well as in other regions with similar climate. However, additional field testing in commercial orchards across multiple sites and years is needed before the Gleason-Duttweiler warning system can be recommended for grower use. In the course of this testing, the practical value of the system will need to be determined within the more complex decision matrix of apple production (McCown 2002; Rodriguez et al. 2009; Sherman and Gent 2014).

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Table 1. Least squares means of log-transformed SBFS incidence and number of fungicide cover sprays for five treatments in SBFS warning system evaluations during 2010 and 2011 (Trial 1)

		2010		2011	
Treatment	**Fungicide regime**	**Log SBFS incidence**[a]	**No. of cover sprays**[b]	**Log SBFS incidence**[a]	**No. of cover sprays**[b]
Warning system	Conventional[c]	-0.19 b	5	-0.54 b	4
Warning system	Reduced-risk[d]	-0.29 b	5	-0.35 b	4
Warning system	Reduced-risk[e]	-0.14 b	5	-0.11 b	4
Calendar-based	Conventional[c]	-0.15 b	8	-0.40 b	6
Control	None after 1st cover	4.47 a	0	2.46 a	0

[a]Least squares means within column followed by the same letter are not significantly different, LSM (P<0.05).

[b]Number of fungicide sprays after first-cover spray.

[c]Captan 80WDG + Topsin® M 4.5FL.

[d]Pristine® 38 WG (only boscalid in the mixture is registered by U.S. EPA as reduced-risk, not pyraclostrobin (www.epa.gov)) was applied for first- and second-cover sprays, followed by Captan 80WG + Topsin® M 4.5FL for subsequent cover sprays until harvest.

[e]Flint® 50 WG (EPA-registered as a reduced-risk fungicide) was applied for first- and second-cover sprays, followed by Captan 80WG + Topsin® M 4.5FL for subsequent cover sprays until harvest.

Table 2. Least squares means, marketable apple and number of fungicide cover sprays for five treatments in SBFS warning system evaluations from 2013 to 2015 (Trial 2)

		2013			**2014**			**2015**		
Treatment	**Fungicide regime**	**Log SBFS incidence**[a]	**Marketable apples (%)**	**No. of cover sprays**[b]	**Log SBFS incidence**[a]	**Marketable apples (%)**[a]	**No. of cover sprays**[b]	**Log SBFS incidence**[a]	**Marketable apples (%)**[a]	**No. of cover sprays**[b]
Warning system	Conventional[c]	-0.01 a	100	2	0.32 b	100 a	4	1.15 b	98 a	4
Warning system	Reduced-risk[d]	-0.49 a	100	2	0.14 b	99 a	4	1.50 b	98 a	4
Calendar-based	Conventional[c]	-0.45 a	100	7	0.74 b	100 a	5	0.87 b	99 a	6
Calendar-based	Reduced-risk[d]	-0.60 a	100	7	0.39 b	100 a	5	0.76 b	99 a	6
Control	None after 1st cover	1.13 a	100	0	3.11 a	93 a	0	4.56 a	44 b	0

[a]Least squares means within column followed by the same letter are not significantly different, LSM (P<0.05).

[b]Number of fungicide spray after first-cover spray.

[c]Captan 80WDG + Topsin® M 4.5FL.

[d]Captan 80WG + Flint® 50 WG (EPA-registered as a reduced-risk fungicide) (applied twice), Captan 80WDG + Prophyt® (EPA-registered as a biofungicide) (applied three times), then Captan 80WG+Flint® 50 WG (applied twice).

Table 3. Three economic analyses used to evaluate the RH-based warning system in Iowa based on Trial 2 results

Analysis	**Formula**	**Assumptions**
Equivalent annual cost[a]	$= \frac{Asset\ Price}{1 - {}^{1}/_{(1+r)^{t}}} * r$	• r, cost of capital 5% • t, 3-year life expectancy of the weathering monitoring hardware
Cost ratio for year i	$= \frac{Average\ cost\ in\ year\ i\ for\ the\ warning\ system}{Average\ cost\ in\ year\ i\ for\ the\ calendar - based\ system\ for\ an\ orchard}$	• Orchard size >5 hectares doubles the device cost for warning system.
Relative cost efficiency ratio for year i[b]	$= \frac{\%\ marketable\ apple\ for\ year\ i / cost\ for\ warning\ system\ for\ year\ i}{\%\ marketable\ apple\ for\ year\ i / cost\ for\ calendar - based\ system\ for\ year\ i}$	

Table 4. Weather inputs and key dates for calendar-based and warning system treatments from 2013 to 2015 (Trial 2)

	Year		
Category and input	**2013**	**2014**	**2015**
Orchard data			
Mean temperature (°C)[a]	21.9	21.0	20.8
Mean RH (%)[b]	75.2	81.3	82.9
First harvest date[c]	4 Sep	27 Aug	2 Sep
Final harvest date[d]	15 Oct	1 Oct	8 Oct
Cumulative rainfall[e] (mm)	163.1	410.5	541.3
Calendar-based treatments			
Date of first-cover spray	28 May	5 Jun	27 May
Date of second-cover spray[f]	10 Jun	21 Jun	10 Jun
Days from first- to second-cover spray	14	17	15
Warning-system treatments using ≥90% RH threshold			
Date of first-cover spray	28 May	5 Jun	27 May
Date of second-cover spray[g]	9 Aug	9 Jul	9 Jul
Days from first- to second-cover sprays	74	35	44
Warning-system with ≥90% *vs.* ≥97% RH threshold			
Date of ≥90% RH threshold[h]	23 Jul	7 Jul	29 Jun
Date of ≥97% RH threshold[h]	26 Jun	27 Jun	20 Jun
Days difference between ≥90% and ≥97% RH threshold	27	10	9

[a]Mean temperature from first-cover spray to day on which threshold was reached.

[b]Mean RH from first-cover spray to day on which threshold was reached.

[c]First cultivar harvested (McIntosh).

[d]Final cultivar harvested (Red Delicious).

[e]Cumulative rainfall from first-cover spray to day on which cv. McIntosh was harvested (www.mesonet.agron.iastate.edu).

[f]Fungicide sprays were applied according to pre-scheduled timing (every 10 to 14 days from first cover to harvest).

[g]Fungicide spray was applied when the RH threshold was reached.

[h]Date when either of the paired RH sensors reached the threshold.

511

Table 5. Cost analysis of each treatment from 2013 to 2015 in a 0.52 ha. apple orchard in Gilbert, IA

					Cost Components ($)[a]			
Year	**Treatment**	**Fungicide regime**	**No. of cover sprays[b]**	**Total cost ($)**	**Monitoring equipment[c]**	**RH monitoring and spraying labor[d]**	**Fungicide[e]**	**Fuel[f]**
2013	Warning system	Conventional	2	285.26	196.46	60	26.70	2.10
	Warning system	Reduced-risk	2	287.96	196.46	60	29.40	2.10
	Calendar-based	Conventional	7	275.80	0	175	93.45	7.35
	Calendar-based	Reduced-risk	7	292.60	0	175	110.25	7.35
	Control	None after 1st cover	0	0	0	0	0	0
2014	Warning system	Conventional	4	364.06	196.46	110	53.40	4.20
	Warning system	Reduced-risk	4	364.06	196.46	110	53.40	4.20
	Calendar-based	Conventional	5	197.00	0	125	66.75	5.25
	Calendar-based	Reduced-risk	5	211.10	0	125	80.85	5.25
	Control	None after 1st cover	0	0	0	0	0	0
2015	Warning system	Conventional	4	364.06	196.46	110	53.40	4.20
	Warning system	Reduced-risk	4	364.06	196.46	110	53.40	4.20

Calendar-based	Conventional	6	236.40	0	150	80.10	6.30
Calendar-based	Reduced-risk	6	251.85	0	150	95.55	6.30
Control	None after 1st cover	0	0	0	0	0	0

[a]Based on treatments tested on a 0.52-ha apple field at the Iowa State University Horticulture Research Station, Gilbert, IA.

[b]Number of fungicide spray after first-cover spray.

[c]Equivalent annual cost based on the total device price of $535, including: two Watchdog A150 Temp/RH loggers ($338), one A-series PC-cable ($29), and two radiation shields ($168). Cost for laptop computer (for data downloading) was not included in the analysis.

[d]RH monitoring required 30 minutes per week and fungicide spraying required 75 minutes/spray at $20/hour labor cost.

[e]Price for each fungicide in July 2016 was as follows: $37.46/kg for Topsin® M 4.5FL; $20.81/kg for Captan 80WDG, $439.24/L for Flint® 50WG, and $13.11/liter for ProPhyt®.

[f]1.89 liter/spray, $1.11/liter.

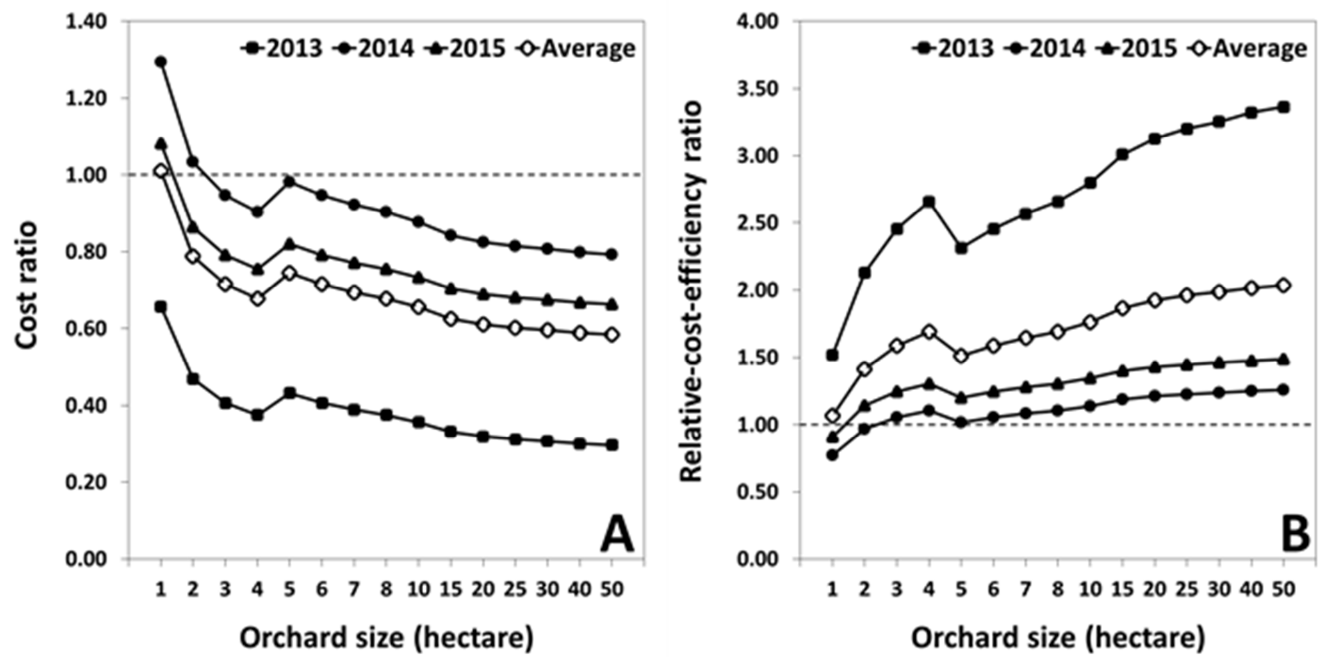
Figure 1. Economic analysis showing ratio of Gleason-Duttweiler SBFS warning system:calendar-based system for different orchard sizes, based on 2013 to 2015 trials. **A**. Cost ratio. **B**. Relative cost-efficiency ratio.

Figure 2. Scatter plot of SBFS incidence from each tree (50 apples) for each treatment in Trial 1. **A**. 2010. **B**. 2011.

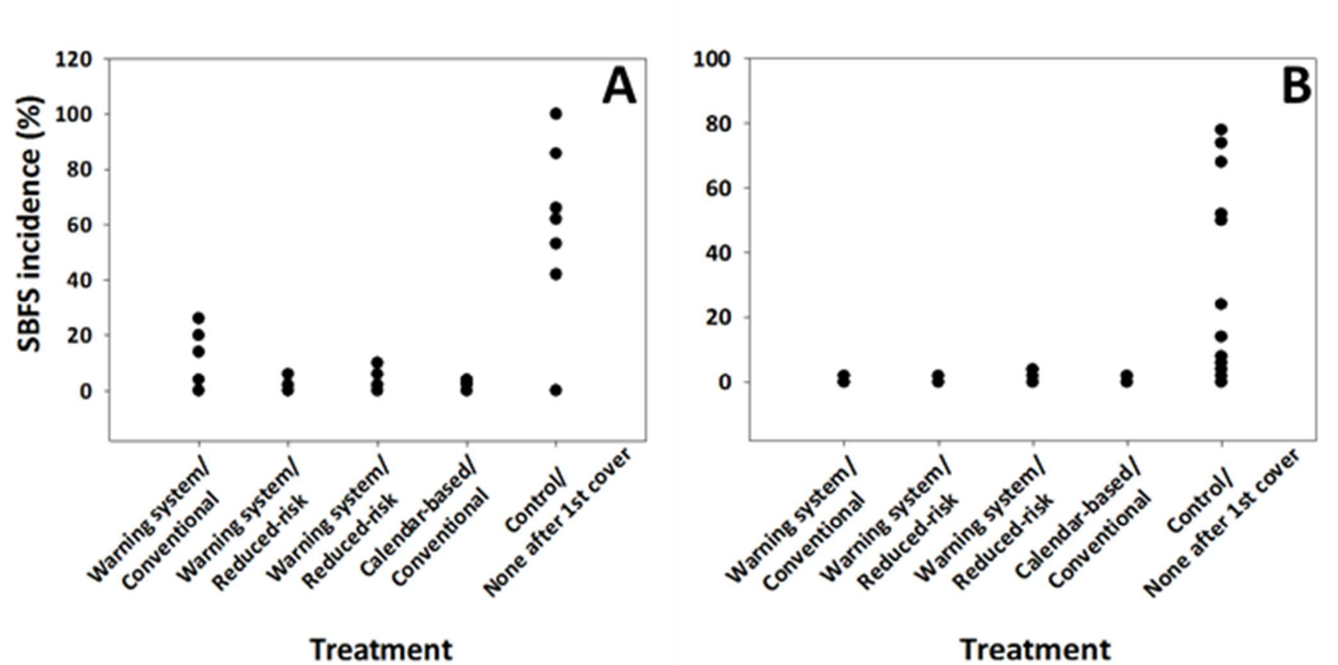
Figure 3. Scatter plot of SBFS incidence from each tree (50 apples) for each treatment in Trial 2. **A**. 2013. **B**. 2014. **C**. 2015.

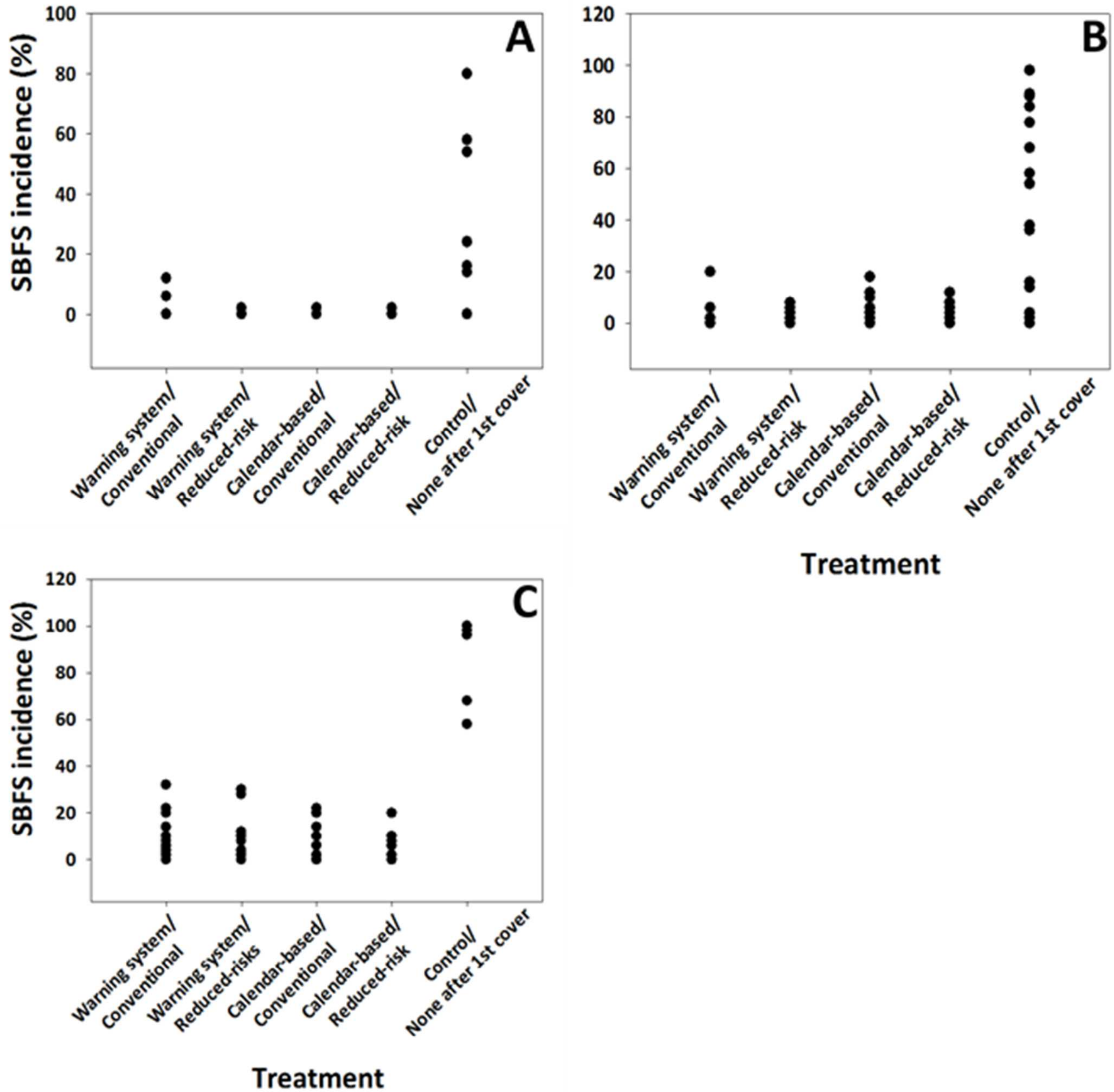
Supplementary Figure S1. Schematic view of 0.52-ha apple orchard at the Iowa State University Horticulture Research Station.

Supplementary Figure S2. Scatter plot of percent marketable apples from each tree (50 apples) for each treatment in each year of Trial 2. **A**. 2013. **B**. 2014. **C**. 2015.



2013
2014
2015
Average
Cost ratio
A
Orchard size (hectare)
Relative-cost-efficiency ratio
B
Orchard size (hectare)


A
SBFS incidence (%)
120
100
80
60
40
20
0
Warning system/ Conventional
Warning system/ Reduced-risk
Warning system/ Reduced-risk
Calendar-based/ Conventional
Control/ None after 1st cover
Treatment
B
100
80
60
40
20
0
Warning system/ Conventional
Warning system/ Reduced-risk
Warning system/ Reduced-risk
Calendar-based/ Conventional
Control/ None after 1st cover
Treatment


A
B
C
SBFS incidence (%)
Warning system/ Conventional
Warning system/ Reduced-risk
Warning system/ Reduced-risks
Calendar-based/ Conventional
Calendar-based/ Reduced-risk
Control/ None after 1st cover
Treatment

Supplementary Table S1. Mean SBFS incidence for five treatments in SBFS warning system evaluations during 2010 and 2011 (Trial 1)

		2010	2011
Treatment	**Fungicide regime**	**SBFS incidence (%)**	**SBFS incidence (%)**
Warning system	Conventional[a]	4.3	0.1
Warning system	Reduced-risk[b]	1.1	0.4
Warning system	Reduced-risk[c]	1.9	0.7
Calendar-based	Conventional[a]	0.7	0.1
Control	None after 1st cover	80.6	31.5

[a]Captan 80WDG + Topsin® M 4.5FL.

[b]Pristine® 38 WG (only boscalid in the mixture is registered by U.S. EPA as reduced-risk, not pyraclostrobin (www.epa.gov)) was applied for first- and second-cover sprays, followed by Captan 80WG + Topsin® M 4.5FL for subsequent cover sprays until harvest.

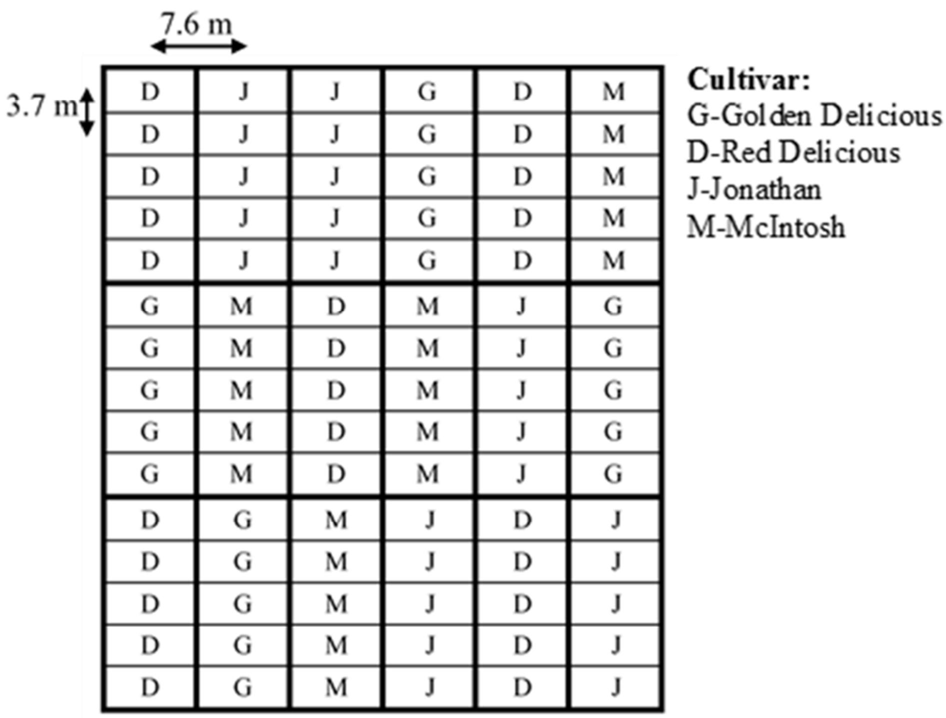
[c]Flint® 50 WG (EPA-registered as a reduced-risk fungicide) was applied for first- and second-cover sprays, followed by Captan 80WG + Topsin® M 4.5FL for subsequent cover sprays until harvest.

Supplementary Table S2. Mean SBFS incidence for five treatments in SBFS warning system evaluations from 2013 to 2015 (Trial 2)

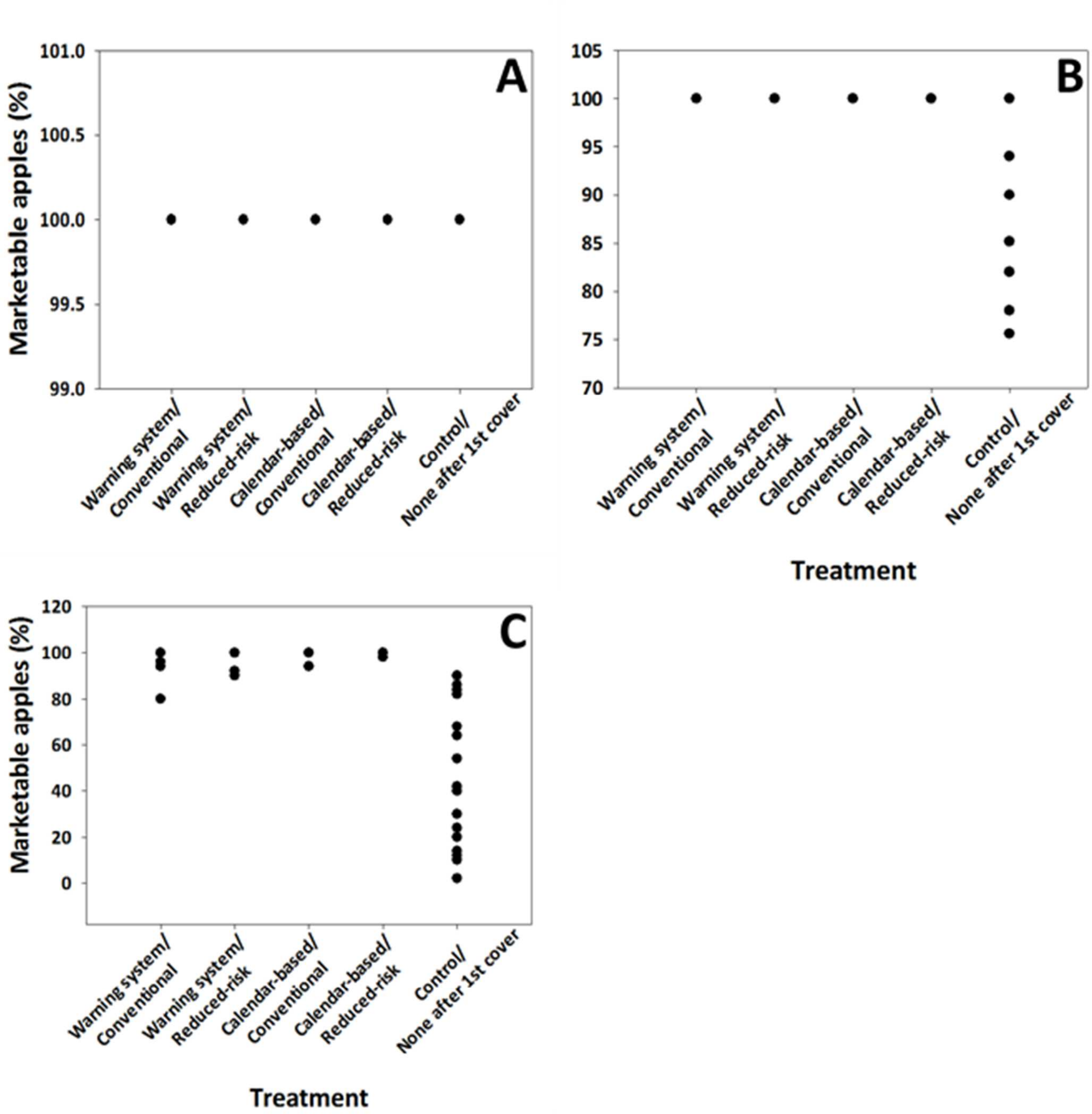
Treatment	Fungicide regime	2013	2014	2015
		SBFS incidence (%)	SBFS incidence (%)	SBFS incidence (%)
Warning system	Conventional[a]	2.0	2.8	8.0
Warning system	Reduced-risk[b]	0.1	1.7	7.7
Calendar-based	Conventional[a]	0.1	4.0	6.5
Calendar-based	Reduced-risk[b]	0.4	2.8	4.2
Control	None after 1st cover	16.4	46.3	92.9

[a]Captan 80WDG + Topsin® M 4.5FL.

[b]Captan 80WG + Flint® 50 WG (EPA-registered as a reduced-risk fungicide) (applied twice), Captan 80WDG + Prophyt® (EPA-registered as a biofungicide) (applied three times), then Captan 80WG + Flint® 50 WG (applied twice).



Supplementary Figure S1. Schematic view of 0.52-ha apple orchard at the Iowa State University Horticulture Research Station.



Supplementary Figure S2. Scatter plot of percent marketable apples from each tree (50 apples) for each treatment in each year of Trial 2. **A**. 2013. **B**. 2014. **C**. 2015.

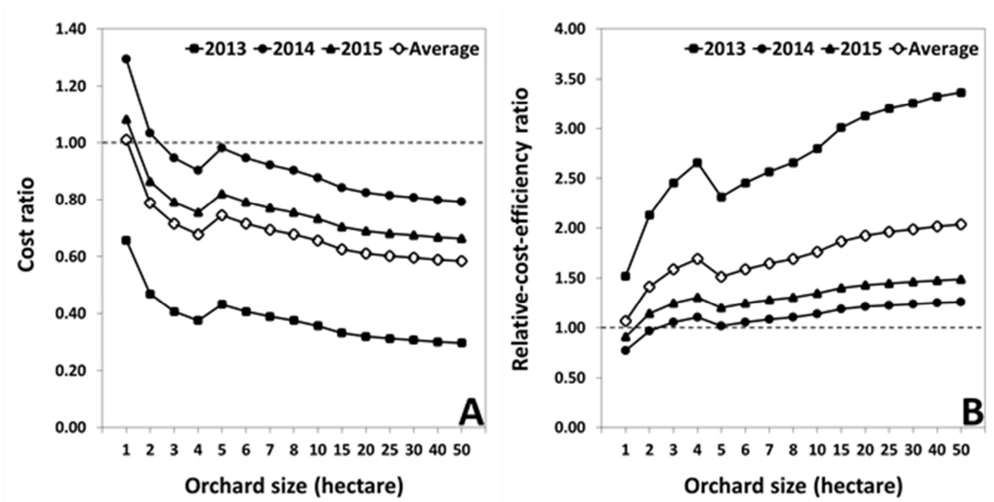


Figure 1. Economic analysis showing ratio of Gleason-Duttweiler SBFS warning system:calendar-based system for different orchard sizes, based on 2013 to 2015 trials. A. Cost ratio. B. Relative cost-efficiency ratio.

178x88mm (96 x 96 DPI)

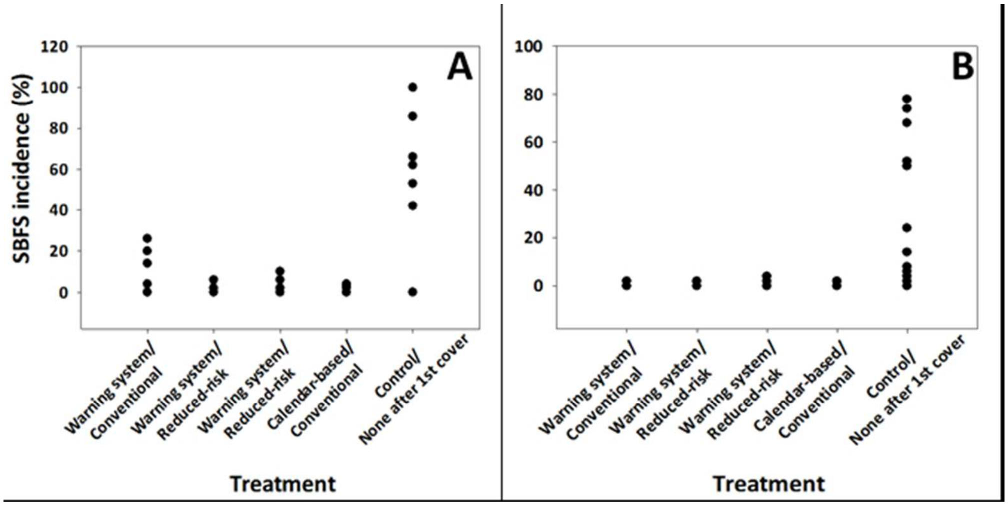


Figure 2. Scatter plot of SBFS incidence from each tree (50 apples) for each treatment in Trial 1. A. 2010. B. 2011.

178x88mm (96 x 96 DPI)

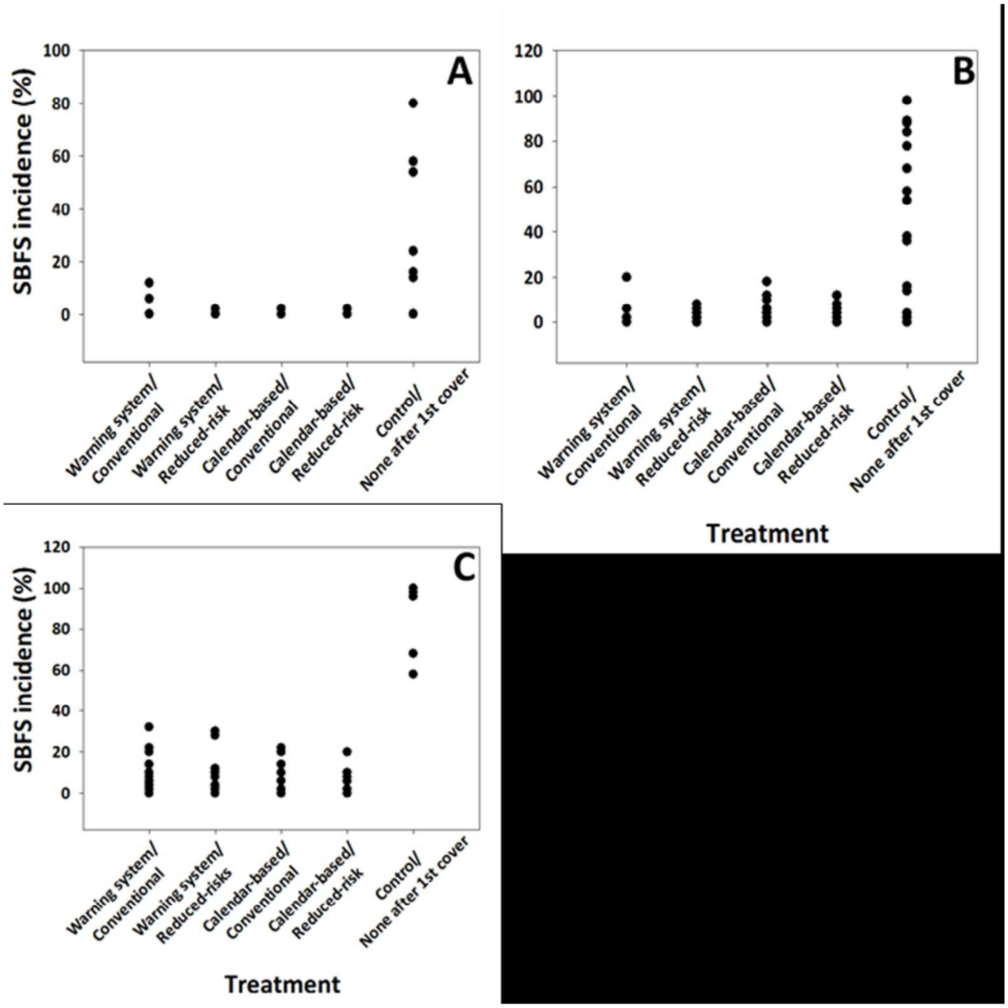
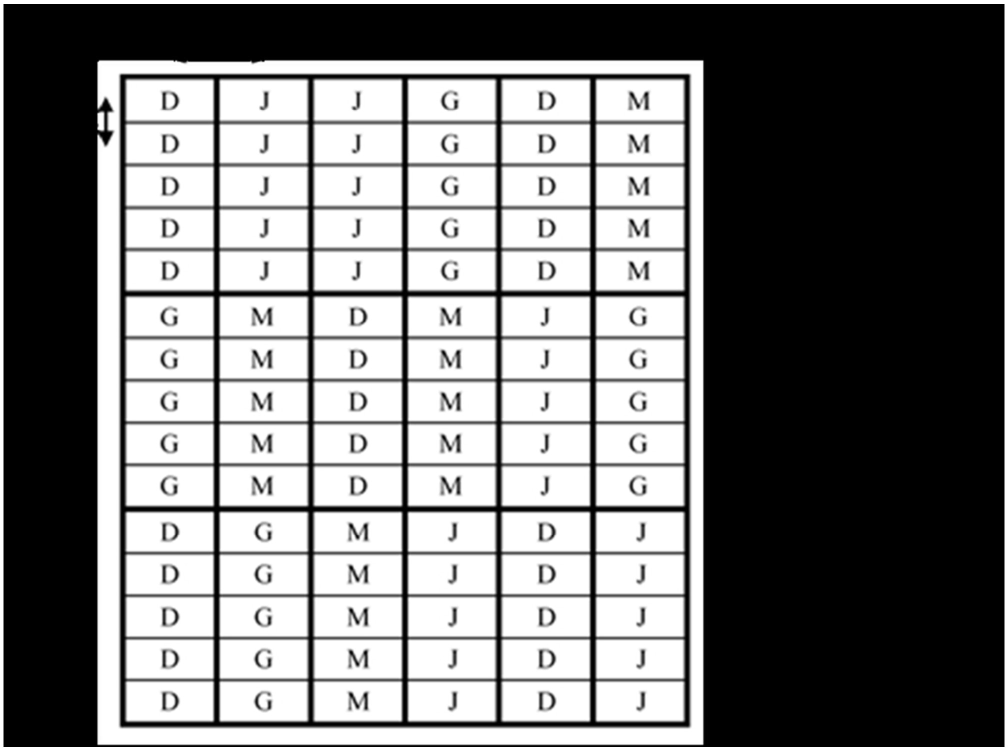


Figure 3. Scatter plot of SBFS incidence from each tree (50 apples) for each treatment in Trial 2. A. 2013. B. 2014. C. 2015.

178x178mm (96 x 96 DPI)



Supplementary Figure S1. Schematic view of 0.52-ha apple orchard at the Iowa State University Horticulture Research Station.

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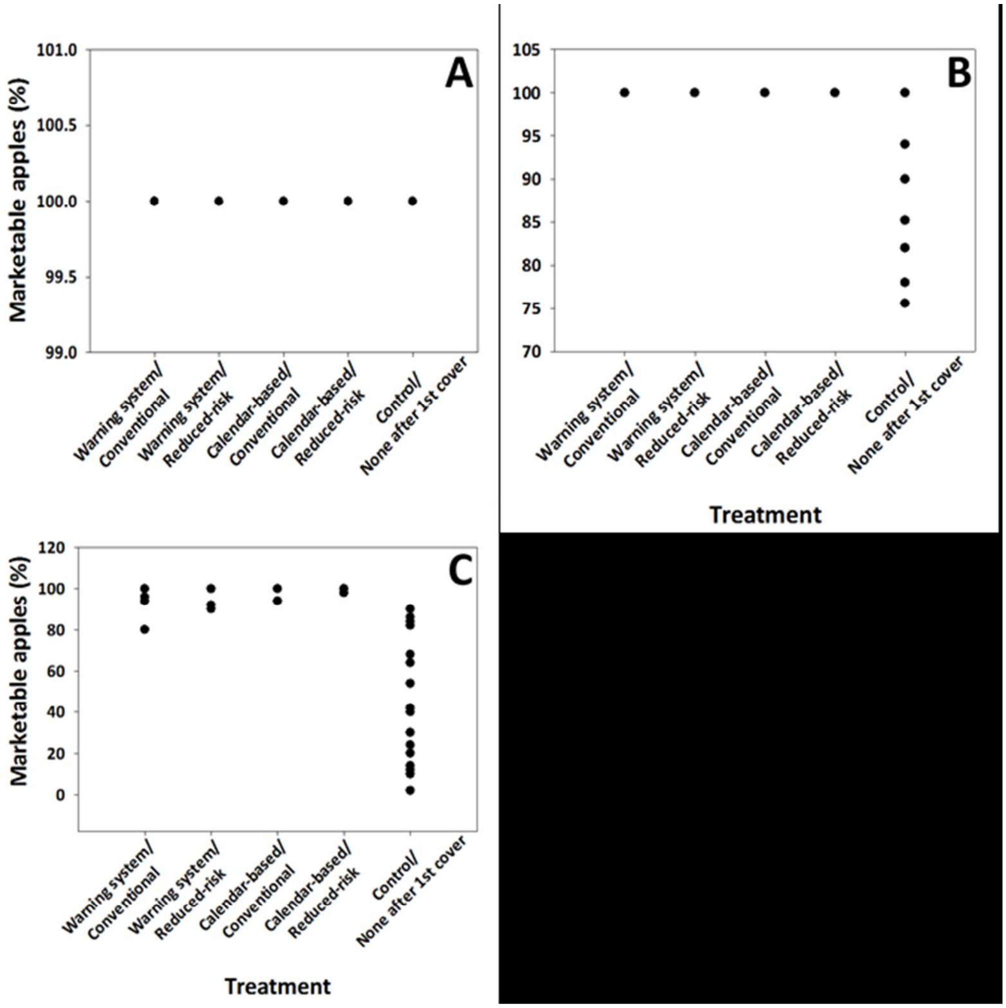

Supplementary Figure S2. Scatter plot of percent marketable apples from each tree (50 apples) for each treatment in each year of Trial 2. A. 2013. B. 2014. C. 2015.

178x178mm (96 x 96 DPI)